

CAUSES OF MULTIMODAL MOISTURE CONTENT FREQUENCY DISTRIBUTIONS AMONG RICE KERNELS

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ABSTRACT. *In a greenhouse study, individual kernel moisture content was measured for the main stem, and for primary, secondary, and tertiary tillers in five plants (replicates) per harvest day for nine harvest days. One of the objectives was to determine whether the multimodal distribution of number of kernels versus moisture content observed in the field (Kocher et al., 1990; Siebenmorgen et al., 1992) could be attributed to the location where the seed was borne with respect to main stem or tillers. Results and analysis of the data revealed that the main stem and primary and secondary tillers exhibited very similar, multimodal distribution patterns. Therefore, the different moisture content peaks or "modes" could not be explained by main stem or tiller influence. However, a possible explanation of the multimodal frequency distribution pattern, based upon the change in moisture content of an individual rice kernel during its development, is presented. Keywords. Moisture content, Rice, Moisture content distribution, Rice kernel development.*

The economic return of a rice crop is directly determined by the head rice yield (HRY), which is related to the precipitation and crop moisture content (MC) histories (all MCs are expressed on a wet basis). Head rice is defined as those rice kernels that are 3/4 or more of the original kernel length after milling. Head rice yield is the ratio of head rice weight after complete milling to rough rice weight before milling, expressed as a percentage. The revenue obtained for broken milled rice is approximately half that for head rice (Kocher et al., 1990). Studies have shown that as the average crop MC decreases during the harvest period, HRY reaches a maximum and then can decrease (Lu et al., 1992). Furthermore, MC of the crop, combined with ambient weather conditions late in the growing season, were shown to affect HRY (Siebenmorgen et al., 1992; Lu et al., 1992). As a rice kernel matures, the MC of the kernel generally decreases. Furthermore, kernels on a plant do not all mature at the same time, but vary considerably in MC during early stages of the growing season and less at later stages of the growing season (Kocher et al., 1990). If rain occurs, the rice kernels below a critical MC are likely to rewet and fissure, ultimately resulting in more broken rice (lower HRYs) when milled (Siebenmorgen et al., 1992). Since there is a greater percentage of kernels below the critical MC at the end of the growing season, rain at that time can cause much more crop damage than earlier precipitation. Thus, there is an incentive to predict the

kernel MC frequency distribution throughout the harvest period, since knowledge of the percentage of kernels below the critical rewetting threshold at any given time could be used to develop a model aimed at predicting and explaining the consequences of rain during the harvest season. Such a model could in turn aid in predicting the optimum harvest date for maximizing profits.

In previous studies (Kocher et al., 1990; Siebenmorgen et al., 1992), frequency distribution graphs revealed that kernel MCs fell in up to three groups or modes during the harvest season. In this article, two possible explanations for these modes were explored.

The first explanation was related to rice plant structure. Most kernels are formed on the main stem, the primary tiller and the secondary tiller of the rice plant. Furthermore, these three structures emerge successively. Thus, the first speculation explored was that the three modes could be explained by the emergence and development of kernels on these three plant structures.

The second explanation explored was related to individual rice kernel development. On a rice plant, kernels do not all emerge at the same time. Anthesis or flowering usually starts at the top of the panicle and ends at the bottom. A typical anthesis pattern is shown in figure 1. Since some rice panicles emerge earlier than others, the process of flowering can occur over a period as long as 15 days (Luh, 1991). Yoshida (1981) recorded the changes in MC at successive stages of growth for two varieties of rice under three different temperature regimes. Figure 2 presents one of the six plots, variety 'IR10' at one temperature regime. A characteristic shared by the six plots and illustrated in figure 2 was that there were periods during growth and maturation when the MC remained relatively constant compared to other periods.

Because individual kernels emerge at different times, if they all followed similar MC versus time relationships as depicted in figure 2, when the individual MCs for all kernels were tallied, the MC frequency distribution would display a mode corresponding to each plateau in the individual kernel MC versus time curve. In other words, if

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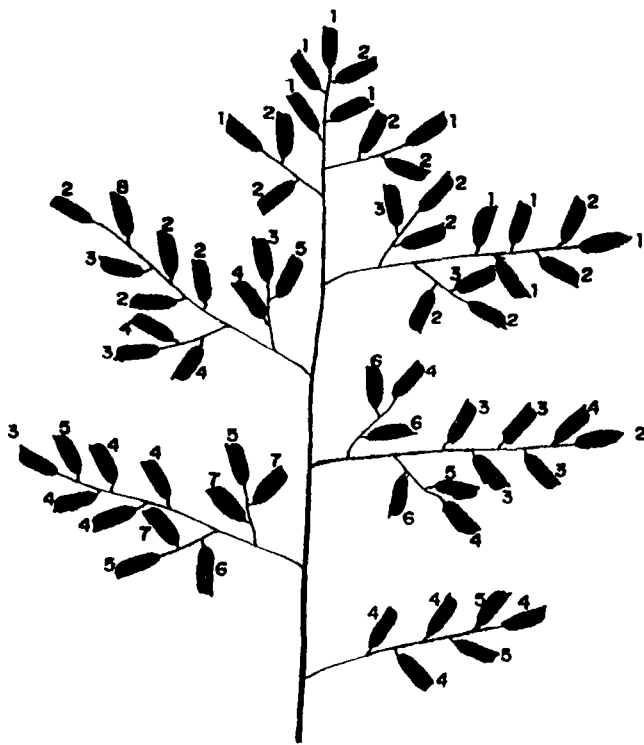


Figure 1—Anthesis or flowering pattern of a rice panicle with numerals indicating day of flowering (Luh, 1991).

individual kernels remained at certain MCs for extended periods of time during development, when the MCs of the individual kernels were compiled, more kernels would tend to fall around these “plateau” MCs than at others. Therefore, it is possible that the multimodal MC distribution observed could be explained by MC plateaus that occurred during maturation of the individual kernels.

MATERIALS AND METHODS

MOISTURE CONTENT FREQUENCY DISTRIBUTION AS A FUNCTION OF TILLER TYPE

A greenhouse experiment was planted in December of 1989 and terminated with the final grain harvest in June of

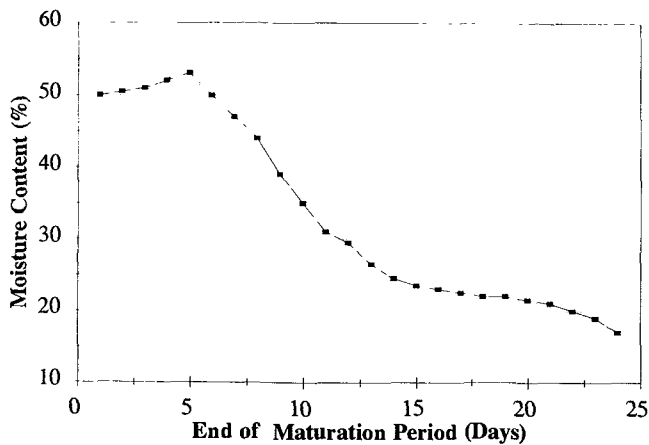


Figure 2—Water content of rice variety ‘IR10’ during growth and maturation under one temperature regime (Yoshida, 1981).

Table 1. Hypothetical moisture content (% w.b.) trend of rice kernels after flowering

Days after First Day of Emergence	Day of Emergence							
	1	2	3	4	5	6	7	8
Emergence	10	16	10	14	7	4	3	1
1	50							
2	51	50						
3	51	51	50					
4	52	51	51	50				
5	53	52	51	51	50			
6	50	53	52	51	51	50		
7	47	50	53	52	51	51		50
8	44	47	50	53	52	51	51	50
9	39	44	47	50	53	52	51	51
10	35	39	44	47	50	53	52	51
11	31	35	39	44	47	50	53	52
12	30	31	35	39	44	47	50	53
13	27	30	31	35	39	44	47	50
14	25	27	30	31	35	39	44	47
15	24	25	27	30	31	35	39	44
16	23	24	25	27	30	31	35	39
17	23	23	24	25	27	30	31	35
18	22	23	23	24	25	27	30	31
19	22	22	23	23	24	25	27	30
20	22	22	22	23	23	24	25	27
21	21	22	22	22	23	23	24	25
22	20	21	22	22	22	23	23	24
23	19	20	21	22	22	22	23	23
24	17	19	20	21	22	22	22	23
25		17	19	20	21	22	22	22
26			17	19	20	21	22	22
27				17	19	20	21	22
28					17	19	20	21
29						17	19	20
30							17	19
31								17

1990. The MC of every kernel by tiller type on each of five plants (five replicates) was measured on nine days during the harvest period: 30 May, and 1, 4, 6, 8, 11, 13, 15, and 18 June. Therefore, a total of 45 plants were sampled.

Each plant was grown in 0.2-m diameter, 5.8-L plastic pots filled with 4.7 kg of Sharkey silty clay soil (Vertic Haplaquepts, pH 6.7). Plants were arranged in randomized complete blocks with five replications on a single greenhouse bench. Prior to flooding, plants were assigned to replicates by size, the largest plants being selected for the first replication and the remainder being grouped progressively down to the smallest plants, which were assigned to the fifth replication. Therefore, replicates were blocked by size and the treatment was the harvest date. The harvest date was independent of plant size because one randomly selected plant from each of the five replications was harvested on each date.

The long-grain rice cultivar used in the experiment was ‘Alan’. Conditions of the experiment were arranged so as to maximize tillering and differences in tiller ages within plants. Pots were fertilized with a dilute solution of urea (730 mg N per pot) at flooding, at panicle differentiation

Table 2. Mean MC and standard deviation of all kernels harvested on each harvest day

Harvest Date	Moisture Content (% w.b.)	
	Mean	Standard Deviation
30 May	30.7	6.6
1 June	26.7	7.8
4 June	26.2	7.4
6 June	23.8	6.5
8 June	21.8	5.6
11 June	19.1	4.5
13 June	18.4	3.9
15 June	18.5	4.1
18 June	19.7	4.2

Table 3. Average number of panicles and kernels per plant component for all plants harvested throughout the season

Plant Component	Panicles Per Plant Component	Kernels Per Plant Component
Main Stem	1.00	200
Primary Tiller	6.00	893
Secondary Tiller	9.07	915
Tertiary Tiller	2.63	99

(365 mg N per pot), and seven days after panicle differentiation (365 mg N per pot). Temperatures in the greenhouse were maintained between 14° and 20° C between planting and flooding. From the date of flooding onward, temperatures were maintained between 20° and 30° C until the final five harvest dates of the experimental period when temperatures ranged between 30° and 44° C. Supplemental radiation was supplied for the plants by metal halide lamps (MGS Batwing Maxi-Gro HID Plant Grower; GTE/Sylvania, Fall River, MA 02734). The lamps were operated from 5:00 A.M. to 7:00 P.M. daily. The irradiance without sunlight was measured to be 150 to 200 $\mu\text{mol m}^{-2} \text{s}^{-1}$ at the top of the canopy. The bench was progressively lowered to maintain the height of the lamps above the plants at 1.5 m. On clear days, lamps were turned off from 9:00 A.M. to 3:00 P.M.

Beginning at flooding, individual tillers arising from each plant were tagged, mapped, and identified as to order of emergence and tiller type. At harvest, the stubble and panicle were separated for each culm that produced a panicle. Kernels were separated from the panicle by the same person during each harvest to avoid differences in discarding kernels that were judged to be unfilled. The number of kernels, weight of kernels, and weight of stubble were recorded for each main stem and tiller bearing a panicle. Individual kernel MCs were determined with a model CTR-800 (Shizuoka Seiki Co., Ltd., 4-1 Yamana, Fukuroi, Shizuoka, Japan 437) single kernel moisture meter.

MOISTURE CONTENT FREQUENCY DISTRIBUTION AS A FUNCTION OF INDIVIDUAL KERNEL MOISTURE CONTENT

The data from figure 1 was combined with the data in figure 2 to form table 1. The first and second columns of

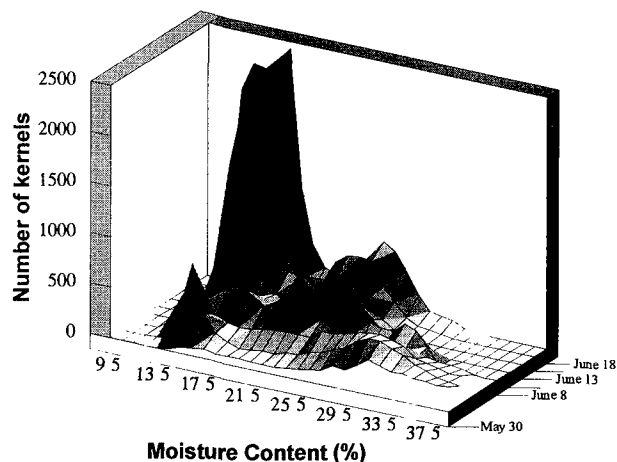


Figure 3—Rice kernel moisture content (% w.b.) distributions on indicated harvest dates in 1990.

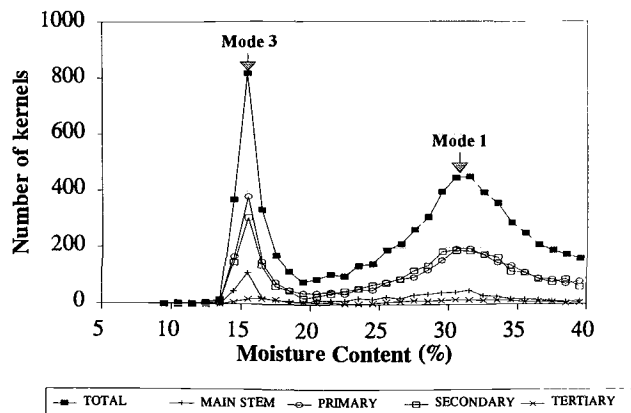


Figure 4—Moisture content distribution on 1 June by main stem and tiller type.

table 1 represent the data extracted from figure 2. In this scenario, the 65 rice kernels in figure 1 were assumed to follow the same MC versus days after flowering relationship presented in figure 2, starting on their days of emergence. On day 3 after the first flower appeared, for instance, 10 kernels with a MC of 50% and 26 kernels with a MC of 51% were theorized. The number of kernels at each MC on each day was then tallied and plotted (fig. 10).

**RESULTS AND DISCUSSION
MOISTURE CONTENT FREQUENCY DISTRIBUTION AS A FUNCTION OF TILLER TYPE**

Table 2 presents the average MC and associated standard deviation of kernels on each harvest day. The average MC steadily decreased throughout the harvest period. The standard deviation also consistently decreased from 1 June to the end of the harvest season.

Table 3 presents the average number of panicles and kernels per main stem and tiller type. The secondary tillers produced approximately 43% of the total number of kernels followed by the primary tillers, which produced approximately 42% of the kernels. The main stem and tertiary tillers produced approximately 9 and 5% of the total number of kernels, respectively.

Figure 3 represents a summary of the MCs of all the kernels measured throughout the study. The distribution of

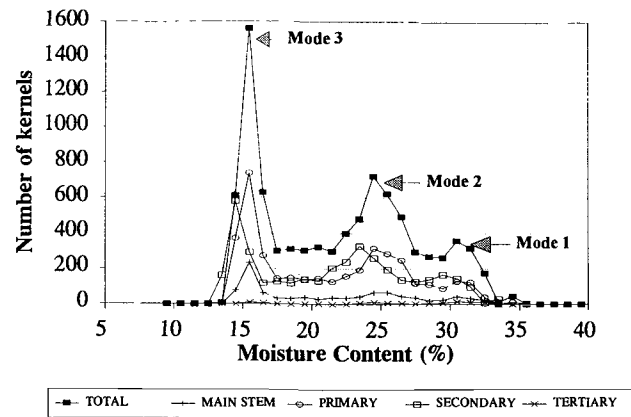


Figure 5—Moisture content distribution on 8 June by main stem and tiller type.

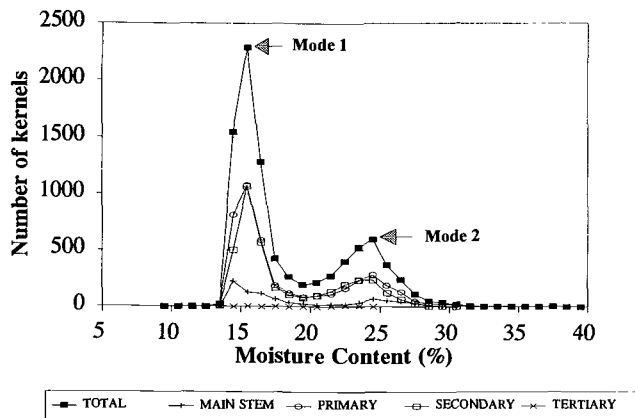


Figure 6—Moisture content distribution on 15 June by main stem and tiller type.

kernel MCs was plotted for each harvest day so that the progression of kernel MCs during the harvest period could be observed. The three modes observable in figure 3 are more explicitly illustrated in figures 4, 5, and 6.

Figures 4, 5, and 6 represent cross-sections of figure 3 on harvest dates 1, 8, and 15 June. These plots include the MC frequency distributions for all the kernels combined (total) and each tiller type. The first mode appeared at MCs between 25 and 40% (figs. 4 and 5), the second mode appeared at MCs between 22 and 28% (figs. 5 and 6) and the third mode appeared at MCs between 10 and 20% (figs. 4, 5 and 6). It was apparent from these figures that the primary and secondary tillers exhibited the same general MC distribution pattern. Because of the relatively small contribution of the main stem and tertiary tillers to the total number of kernels, it was not evident from figures 4, 5, and 6 as to whether or not these tillers also followed the same general pattern as the primary and secondary tillers. However, figures 7, 8, and 9, plots of the cumulative frequency of kernels versus MC for the main stem and the various tiller types measured on 1, 8, and 18 June, indicated that even though there were less kernels on the main stem, the cumulative MC frequency distributions were similar to the other tillers. However, since there were so few kernels collected from the tertiary

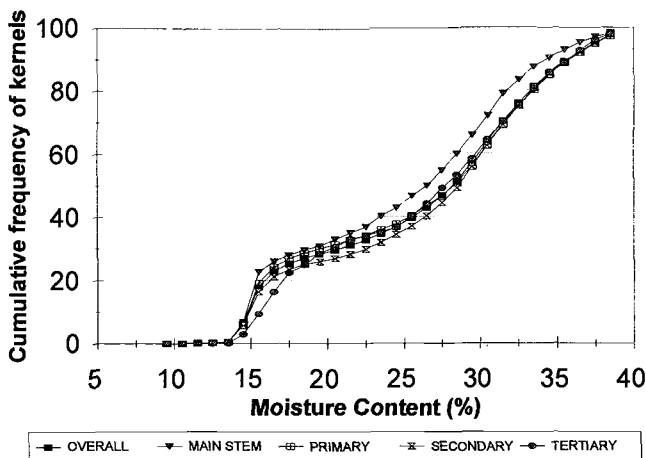


Figure 7—Moisture content cumulative frequency distribution on 1 June by main stem and tiller type.

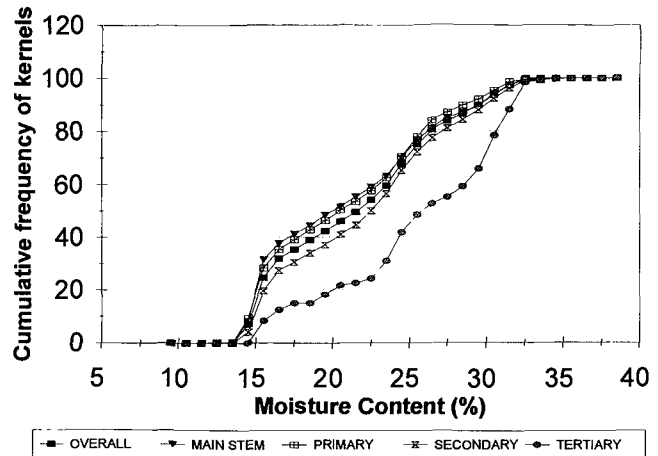


Figure 8—Moisture content cumulative frequency distribution on 8 June by main stem and tiller type.

tillers, it was difficult to determine a typical cumulative frequency distribution pattern. On 8 and 18 June, for instance, only 1.3 and 0.9% of the total number of kernels tallied were from tertiary tillers.

Therefore, it is evident from figures 4 through 9 that the multimodal MC distribution could not be attributed to presence on a plant component, where the seeds were borne with respect to main stem or tillers.

MULTIMODAL MOISTURE CONTENT DISTRIBUTION DERIVATION

The hypothetical distribution of kernel MCs plotted for each day after flowering is presented in figure 10. Figure 10 exhibits two modes, one at a MC of approximately 50.5% and the other at approximately 22.5%. These modes corresponded to the two MC plateaus shown in figure 2. Furthermore, the longest MC plateau at approximately 22.5% shown in figure 2 resulted in the highest peak mode in figure 10.

Figure 10 differs from figure 3 in many ways. First, there are three modes that appear in figure 3 as compared to two in figure 10. This could partially be explained by the fact that figure 10 was generated by data representing the

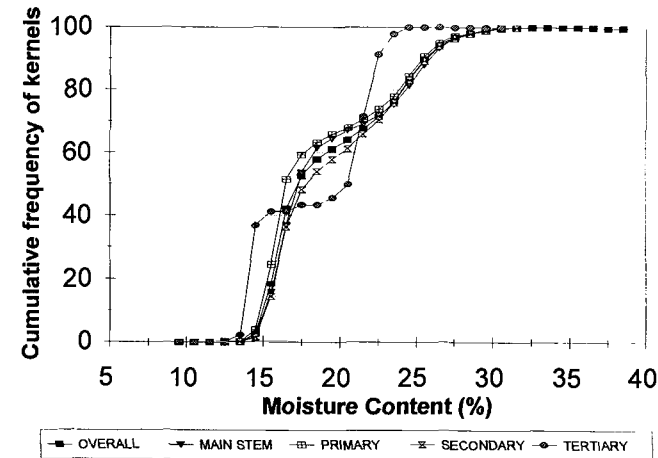


Figure 9—Moisture content cumulative frequency distribution on 18 June by main stem and tiller type.

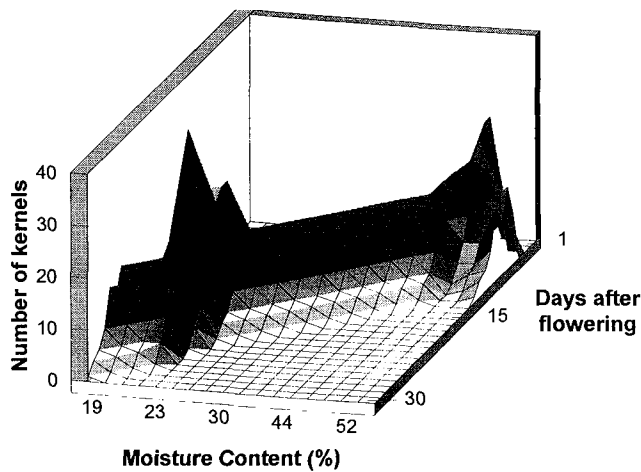


Figure 10—Hypothetical distribution of kernel MCs for each day after flowering.

MC of rice kernels during the initial stages of development and figure 3 was generated by MC data that included the final stages of development. Note that in figure 2, the MC was not measured below approximately 17% while in figure 3, the MC was measured below 10%. Under most harvest conditions, it would have been reasonable to expect the 65 kernels in the scenario to reach an average equilibrium MC below 17%, if given time. This average equilibrium MC would have resulted in a third mode in figure 10 that would have been expected to have the largest peak. This projection is based on the finding that the standard deviation of kernel MCs decreased as average MC decreased from 20 to 10% (Siebenmorgen et al., 1990). Because of the lower standard deviation at lower MCs compared to that at higher MCs, a mode would be expected in the frequency distribution at lower MCs.

A second difference between figures 3 and 10 is that the modes occur at different MCs. This is possibly because the varieties and temperature regimes represented by figures 3 and 10 were different. Examination of the six plots of MC versus days after flowering provided by Yoshida (1981) revealed that the shapes of the six curves are similar, but by no means identical. The plateau MCs, and the times at which these plateaus occurred, varied among the six plots. In other words, the MCs at which the plateaus, hence the expected modes, occurred, differed depending on rice variety and temperature regime. A third, obvious difference between figures 3 and 10 is that the distribution in figure 10 follows a more uniform pattern than that in figure 3. Figure 10 was generated by assuming that the 65 kernels from one panicle followed identical MC trends

during development. It would be reasonable to expect considerably more variation from the thousands of kernels collected from numerous panicles on 45 plants. Not only would the individual kernels be expected to follow slightly different MC trends because of differences in temperature regimes during development, but there are most certainly other, undefined variables that would also cause the individual kernel MC trends to differ somewhat during development.

Further study is needed to evaluate this proposed explanation of multimodal MC frequency distribution among rice kernels, and to understand how rice plant physiology and environmental factors affect the MC trend of individual kernels on a plant.

SUMMARY AND CONCLUSIONS

Kernels from the main stem and all tillers of 'Alan' rice grown in a greenhouse exhibited similar MC frequency distribution patterns that agreed with earlier field observations. Therefore, the different moisture content distribution modes could not be explained by differences in kernel MC patterns among main stem and tillers.

The multimodal MC frequency distribution may possibly be explained by the individual kernel MC plateaus observed during development. When the MCs of all individual kernels are tallied to obtain the MC frequency distribution, modes would tend to form around the plateau MCs. This is because, at any given time, a greater number of kernels would exist at the plateau MCs than at other MC levels.

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